Peat Hazards: compression and failure

Jeff Warburton, Durham University, UK

1. Introduction and scope

Peat is a low density, highly compressible soil that occurs at the surface or may be buried at depth. Peat is essentially an organic, non-mineral soil resulting from the decay of organic matter. In the UK peat deposits are widespread occurring in a wide variety of upland and lowland environments covering all parts of the country (Figure 1). Peat accumulates wherever suitable conditions occur such as in areas of high (excess) rainfall and where ground drainage is poor leading to high water tables. In these waterlogged areas peat develops where the rate of dry vegetative matter accumulation exceeds the rate of decay. Physiochemical and biochemical processes associated with wetland conditions ensure that the accumulating organic matter decays very slowly safeguarding plant structures that remain partially intact for long periods of time (Bell, 2000). In the UK, temperate peat accumulates slowly, typically 0.2 to 1 mm yr^{-1} with local rates varying depending on the topography and hydrology of the peat mire (Charman, 2002).

In the engineering community, peats and organic soils are well known for their high compressibility and long term settlement and, in terms of engineering properties, peat is notoriously difficult to deal with which prompted Powrie (1997, p.16) to comment that: ' ... [organic soils] should not be relied on for anything, except to cause trouble'. To an engineer peat and organic soils are extremely soft, wet, unconsolidated surficial deposits which pose a range of geotechnical problems for sampling, settlement, stability, in situ testing, stabilisation and construction.

The link between the compressibility of peat, its shear strength properties and the risk of bearing capacity failure has not been explored in detail; although the mechanism has been suggested for some peat failures (Lindsay and Bragg, 2005). Peat soils are highly organic, highly compressible and generally possess low undrained strength and their compression / settlement may take a considerable amount of time to stabilise (Huat et al., 2014). Estimating the geotechnical properties of peat is notoriously difficult because published values are relatively few and testing of peat using standard geotechnical tests is fraught with problems (Long, 2005; Dykes Long and Boylan, 2012). Nevertheless, published data (e.g. Dykes 2008) suggest that peat in its undisturbed state has little strength with undrained shear strength values typically varying 5-20 kPa (Long, 2005; Huat et al., 2014). These values vary with the vegetation composition of the peat (particularly fiber content) and the degree of humification; but also are affected by the method of testing (Boylan et al., 2008). Given the high compressibility and low strength of peat, local shear failure may occur when compression / compaction gives rise to vertical displacements which exceed the shear strength (bearing capacity) of the soil (Knappett and Craig, 2012). Shear failure may result where differential displacements of surface peat occur between the area experiencing compression (loading) and the adjacent unloaded peat. In peatlands such sites typically include construction embankments / waste heaps; roads and tracks; and foundations such as wind turbine bases.

Although such failures are local in origin due to the sensitive nature of peat stability, under the right site conditions, these may rapidly propagate in to runaway failures.

Therefore in engineering practice there is a tendency to either avoid construction on these soils or if this is not possible, remove or replace the peat material. However in many countries, including the UK, peat extends over a substantial part of the terrestrial biosphere and peatlands are under increasing pressure for their land use (Figure 1). In lowland areas, particularly in the distal parts of populated deltas and estuaries, peat is common and, due to compaction, may cause land subsidence resulting in damage to infrastructure and land inundation by the sea (van Asselen et al., 2009).

In the UK, there is growing public awareness of the effect of ground conditions on safety and property values and increasing pressure from government to provide environmental information (Royse, 2011). Information about geological hazards and, in particular, the identification of areas which are susceptible to ground movement is needed (BGS, 2010; Figure 1a). The British Geological Survey as part of its UK hazard assessment programme has summarised key information on compressible ground. Their definition is:
"*Ground is compressible if an applied load, such as a house, causes the fluid in the pore space between its solid components to be squeezed out causing it to decrease rapidly in thickness (compress). Peat, alluvium and laminated clays are common types of deposits associated with various degrees of compressibility. The deformation of the ground is usually a one-way process that occurs during or soon after construction*."
Peatlands are considered areas of compressible ground and given the widespread occurrence of peat deposits in the UK (Figure 1b) pose a large potential hazard as a compressible soil.

Peat soils are well known for landslide related hazards and in the UK and Ireland these have been widely reported and documented (Warburton et al., 2004; Dykes and Warburton, 2007; Boylan et al., 2008, Dykes 2009)). However far less is known about the hazards posed by peat compression and the potential problems associated with this. Therefore the aim of this chapter is briefly review the engineering background to peat compression; describe the occurrence of peat soils in the UK; provide examples of the compression hazards associated with these deposits; and consider some of the ways these can be mitigated.

2. Engineering background: peat consolidation and compression

A number of characteristics distinguish peat as an engineering material. These include a high but variable natural water content (c. 500-1500%), very high organic content (loss on ignition 25-100%), significant fibre content, low specific gravity (bulk density), high voids ratio (5-15), high initial permeability, high compressibility and low strength (Edil, 2001). Although peat deposits are highly variable, the degree of humification (the extent of biochemical decomposition of plant remains) is a key factor determining the overall behaviour of peat. Table 1 outlines the von Post scheme of characterising peat deposits based on humification. The end members of this scale go from highly fibrous deposits with insignificant decomposition to amorphous peat with no discernible plant remains. This distinction has been used by MacFarlane and Radford (1965) and MacFarlane (1969) to broadly categorise the engineering behaviour of peat into fibrous and amorphous granular deposits. Further division of the scale in to three categories which characterise broad divisions of peat are based on Fibre content (Fc) and the von Post scale (Edil 2001; Table 1):

1. Fibric: >67% Fc , von Post H1-H3
2. Hemic: 33 - 67% Fc , von Post H4-H6
3. Sapric: <33% Fc, von Post H7-H10

Numerous other classifications of organic soils exist and there is no overall standardised scheme (Myślińska, 2003).

Table 1 near here

In many peats water content by volume may typically vary between 75-98 % (Hobbs, 1986) making peat extremely susceptible to rapid compression. Water may be held in peat in three main phases: intercellular water in macropores; interparticle (intracellular) water in micropores; and adsorbed or bound water. The typical proportions of these will vary depending on the peat type. Commonly, active bog peat exhibits a two-layered structure (Ivanov, 1981; Ingram, 1982). The lower layer, which is in general continually saturated and is composed of older, more humified peat, is known as the catotelm; whilst the more aerated upper layer, which typically lies above the lowest water table limit, is called the acrotelm.

Figure 2a shows the gas, water and solid components, and their volume relationships, for a peat core under Sphagnum vegetation (Rydin and Jeglum, 2006). In the upper layers (acrotelm) gas volume near the surface is around 85% but decreases to zero at just below the water table. Below the water table, extracellular and intracellular water make up 90% of the volume. The proportion of solid peat increases with depth as the partial decayed plant material becomes increasingly humified and compressed. Total pore spaces in peat vary between 78-93 % (Rydin and Jeglum, 2006) with porosity decreasing as humification, bulk density and the degree of compaction increase. The hydrological functioning of peat is strongly controlled by the structure of the peat matrix which in turn is highly susceptible to compression and deformation (Price and Schlotzhauer, 1991). This novel property of peat means that volume changes to a peat mass may occur over timescales which are characteristic of hydrological events due to rapid readjustments of the peat pore structure (Kennedy and Price, 2005).

The presence of gas trapped in peat has important implications for the surface hydrology of peat bogs affecting both microclimate and ecohydrology (Strack et al., 2006). Equally, the physical properties of peat itself, including permeability, rate of consolidation and pore pressure, are also affected (Macfarlane, 1969). Trapped gas arises due to the slow decomposition of organic matter below the water table which generates CH_4 (methane - marsh gas) and lesser amounts of N and CO_2. Typically the free gas content of peat varies between approximately 5-10 %. Originally biogenic peat gas was thought to originate in deep peat but more recent studies (e.g. Kellner et al., 2005) have demonstrated the presence of shallow pressurised gas pockets in shallow peat (< 1m). Biogenic gases (mainly CH_4) are released from peat by diffusion, by vascular plant transport or ebullition. Recent work by Comas et al. (2014) has shown that biogenic peat gas can be stored in both deep and shallow peat depending on the physical properties of the peat matrix and in particular the presence in the peat stratigraphy of wood layers or abrupt transitions in humification which produce confining layers which temporarily entrap gas. Results comparing the gas content of two bogs, one with woody peat with distinct wood layers and one with a more homogenous peat, showed that the gas contents were 10.8% and 5.7% respectively; the woody peat having the high biogenic gas content (Comas et al., 2014). Although the presence of gas in peat has been recognised for a long time it is only recently with the advent of more sophisticated subsurface mapping technology (e.g. Ground Penetrating Radar) that the extent and distribution of gas is been precisely determined.

2.1 Compression of peat

When peat is subject to an increase of compressive stress (load) the resulting compression or settlement consists firstly of immediate elastic compression (immediate settlement), then primary compression (consolidation) and eventually secondary compression. Peat can compress and consolidate both slowly and rapidly. Slow compression and consolidation allow time for the peat body to respond to the applied load allowing pore water pressures to dissipate and the peat to improve strength and bearing capacity. Alternatively rapid loading, with or without actual compression, may result in a rapid increase in pore water pressure and potential shear failure (Huat et al., 2014). The factors controlling the compressibility of peat include permeability, natural water content, void ratio, fibre content, peat structure and inter-particle chemical bonding (Hobbs, 1986; Carlsten, 1988; Mesri and Ajlouni, 2007). Permeability is commonly regarded as the most important engineering property of peat because it controls the rate of consolidation of peat under load and ultimately the strength of the material (Hobbs, 1986).

Over time peat will undergo settlement and Figure 2b shows a schematic time settlement relationship in a soil element undergoing vertical loading (Aysen, 2005). The consolidation (vertical compression) of a soil can be divided into three main stages (Day, 2000):

1. S_i – Initial compression occurs immediately a load is applied and is often estimated from the observed settlement of structures or predicted from the theory of elasticity. If this occurs without any change in the amount of water in the soil (elastic settlement) this may lead to undrained shear deformation or plastic flow due to loading.
2. S_c – Primary consolidation – the compression of the soil under load which occurs as excess pore water pressures dissipate over time.
3. S_s – is a third stage which represents settlement under a constant effective vertical stress and is termed secondary consolidation or secondary compression. This is the component of settlement which occurs after all the excess pore pressures have dissipated and is sometimes referred to as drained creep. The exact mechanisms of secondary consolidation are not well known but appear related to colloid-chemical interactions and small residual excess pore pressures (Aysen, 2005). In peat soils it is generally accepted that this secondary phase of compression is associated with the rearrangement of vegetative fragments and plant structures into a denser matrix (Huat et al., 2014).

The compression index (C_c) describes variation of the voids ratio (e) as a function of the change in effective vertical stress (σ'_v) plotted on a logarithmic scale (Fratta et al., 2007):

$$C_c = \frac{\Delta e}{\Delta \log \sigma'_v} \quad (1)$$

C_c represents the deformation character of a particular soil during primary consolidation (S_c) and in peat soils the plotted curves are very steep indicating a high compression index typically in the range 2 to 15 (Huat et al., 2014). Clays are typically less than 1.0.

Figure 3 shows a plot of percentage natural water content (Wo) and compression index (Cc) for soft clay/silt deposits and peats (from Mesri et al., 1997). Peat deposits are clearly distinguishable from clays and silts, displaying significantly higher natural water content and corresponding compression index values. This relates to the high void ratio that is characteristic of peat. As peat accumulates, high void ratios develop because the plant remains that make up the peat consist of low density particles, fibres and platy structures that create a porous medium with a high water storage capacity (Table 2). Because Cc is directly related to the secondary compression index Cα (Huat et al., 2014) peat deposits also have correspondingly high values of Cα which occurs during secondary consolidation (S_s):

$$C_\alpha = \frac{\Delta e}{\Delta \log t} \qquad (2)$$

Compressibility of peat can therefore be summarised using the Cα/Cc concept (Huat et al., 2014) with peat values showing the highest values of natural soils (Table 2) which appears to depend on the deformability, including the compressibility, of the soil particles / matrix (Mesri et al., 1997).

Table 2 near here

Once loaded, peat settles and consolidates. However, the duration of primary consolidation is very short as a result of the high permeability of the peat deposits and typically this is completed within a few weeks or months (MacFarlane, 1969; Mesri et al., 1997). Hence peat should be loaded slowly so that the reduction in strength due to raised pore water pressures is kept to a minimum; if it is loaded too quickly the peat will shear and fail. Once the initial phase of primary consolidation is complete consolidation proceeds at a much slower rate in a state of secondary compression which is linear with the log of time (Equation 2). The large magnitude and short duration of 'primary consolidation' and the continuous long-term 'secondary compression' distinguish peat soils from their mineral counterparts (MacFarlane, 1969; Fox and Edil, 1996; Fox et al., 1999). The high porosity and low bulk density is thought to account for the dramatic phase of initial compression and the continued deformation of the solid material in the peat results in the long term secondary compression.

Figure 4shows the variation of the water content (%) of UK mire peats with bulk density (Hobbs, 1986) for both bog and fen peats. This serves to emphasise the variability in these properties that commonly occur in UK, which mirrors that from other parts of the world. The presence of mineral soil components (fen peats) generally reduces water content and hence variability, therefore bog peats have higher and more variable water contents. Above about 600% water content the curves in Figure 4 flatten and indicate that the specific gravity and water content do not particularly influence bulk density. The primary influence is the degree of saturation or gas content (Bell, 2000) which in turn depends on the structure and degree of humification of the peat. For example, amorphous granular peat which has undergone greater humification will have a high bulk density and low void ratio resulting in considerable secondary compression. Conversely more fibrous, less humified peats will be more susceptible to primary consolidation (Bell, 2000, Mesri and Ajlouni, 2007).

Variation in the compression index (Cc) with water content (%) is show in Figure 5. This diagram compares UK fen and bog peat and other international examples (Hobbs, 1986). In Figure 5 UK fen peat can be distinguished from UK bog peat and Hobbs (1986) proposed two criteria based on water content (w):

$C_c = 0.0065w$ [bog peat] (3)

$$C_c = 0.008w \qquad \text{[fen peat]} \qquad (4)$$

Although these functions discriminate the two main categories of peat it should be noted there is a transition between the two types, there is considerable scatter around these relationships (Figure 5) and the number and range of samples tested is relatively few. Nevertheless the range of these general relationships are consistent with the behaviour of these types of peat although in the transition zone (e.g.1000% water content) the bog peat has a marginally lower compression index value than fen peat, which is contrary to basic understanding and predictions based on other geotechnical properties (e.g. Liquid limit) (Hobbs, 1986).

This highlights a significant issue in understanding the consolidation behaviour of peat which was identified in early research e.g. Barden (1968). That is, amorphous well humified peats have properties that are more closely related to clay soils rather than fibrous peats whose properties are similar to those just described. However, Berry and Poskitt (1972) and Berry and Vickers (1975) developed a general one dimensional consolidation theory for amorphous and fibrous peat which was validated with experimental testing. Understanding of the engineering properties of fibrous peat and peat engineering in general is now well developed as part of engineering science (Carlsten, 1988; Mesri and Ajlouni, 2007).
More recently work by Mesri and Ajlouni (2007) has demonstrated an approximate linear relationship between C_c with initial water content (w_i):

$$C_c = w_i / 100 \qquad (5)$$

A similar relationship was also noted by and Long and Boylan (2014) who suggest that for Irish peat samples the $C_c = w_i / 125$ was more appropriate which is equivalent to equation (4) above for fen peat.

Therefore, due to these special properties peat differs greatly from other engineering soils inasmuch as initial settlement may occur very quickly leading to rapid and unpredictable failure; primary consolidation may also be large and rapid; and secondary compression, typically negligible in inorganic soils, may be significant over an extended timescale.

3. UK Peatlands: extent and occurrence

In 2011 the UK Joint Nature Conservation Committee provided an assessment of the state of UK Peatlands (JNCC, 2011). This important report summarised the extent, location and condition of peat soil and peatlands, vegetation, land cover, land use, management and a range of environmental influences. In their report, the JNCC estimate peat covers around 4 million km^2 or 3% of the world land area and in Europe, recent estimates of the extent of peatlands are approximately 515,000 km^2 (JNCC, 2011). In the UK the extent of peat is not easily defined because there is little consistent UK wide information on peatlands (maps or statistics) and reconciling the various descriptions and classifications to provide a unified picture of the state of UK peatlands represents a significant challenge (JNCC, 2011).

Different minimum depth and % organic matter content thresholds are used for differentiation between mineral, peaty (organo-mineral) and peat soils in Scotland, England and Wales, and Northern Ireland. In the different soil classification schemes ‘deep peaty soils’ in England Wales and Northern Ireland and Scottish ‘peat soils’ are taken to be broadly equivalent although criteria differ:

- England and Wales: minimum depth 0.4 m, minimum organic matter content 20%
- Northern Ireland: minimum depth 0.5 m, minimum organic matter content 40%
- Scotland: minimum depth 0.5 m minimum % organic matter content 60%

Figure 1b shows the extent of peat and peaty soils in the UK. Although the peat deposits are characterised slightly differently depending on National mapping strategies (e.g. in England they categorised in to four main deposits: deep peaty soils, wasted former deep peats, shallow peaty soils and soils with pockets of deep peat) the map shows the general extent of these soils in the UK. Table 3 summarises the extent of such soils.

Table 3 near here

The striking characteristic of Table 3 is that about a third (79,390 km^2) of the UK is underlain peat or organic rich soils. Clearly there is a strong country bias with the majority of these soils occurring in Scotland but nevertheless significant deposits occur throughout the UK. The distribution clearly reflects areas of high rainfall and poor drainage with a clear bias to the wetter west of the UK. Peat soils typically occur in the wet uplands (North Pennines) and poorly drained lowland (e.g. Somerset levels) (Figure 1b).

Figure 6 is a schematic showing cross-section and plan views of key hydromorphological mire types found in peatlands (Charman 2002). Although a multitude of different peatland classification systems exist the scheme shown in Figure 6 is useful because it provides a general description of the local water table (hydrological) conditions and underlying topography (morphology) prevalent in key mire types typical of temperate environments such as those in the UK. It also provides a basic illustration of the difference between a bog which is fed by rain or snow falling directly on its’ surface and a fen which is influenced by water from outside its own limits (Charman, 2002). Typically, but not exclusively, bogs are ombrotrophic and tend to be acid with low nutrient status; whilst fens are minerotrophic receiving greater mineral nutrients from groundwater and surface runoff and thus have a higher trophic status and are more alkaline (Rydin and Jeglum, 2006). The importance of this in terms of understanding the engineering behaviour of peats is that the topographic and hydrological variety implicit in Figure 6 produces peats which are highly variable in their depth, stratigraphy and microscopic physical properties (Hobbs, 1986); properties that factor in the compression and settlement characteristics of the peat. As suggested by Gould et al. (2002) ‘The ability of the engineer to recognise potential problems due to the presence of compressible organic soils requires familiarity with the geology, topography, and development history of an area.’

4. Geological hazards associated with peat compressibility

There are a range of geological hazards related to compressible soils (BGS, 2010; 2014). However with peat soils the range of hazards might be broadly classified in terms of upland / lowland settings and whether the soil is loaded due to road construction, erecting structures (e.g. buildings in general but in the uplands in particular wind turbines); dumping of waste (e.g. quarrying/ mining); or implementing large engineering schemes (e.g. reservoir construction, gas terminal). Although the peat compression process is similar whether on upland or lowland peat (subject to material constraints) the potential consequences can differ in the two environments due to the depth of the peat and local topography (Figure 6). Here we concentrate on examples from upland environments that illustrate the range of potential hazards associated with compression and bearing capacity failures in upland peats. However, firstly this section begins with some general background on the subsidence of organic soils.

4.1 Subsidence of peat

Compression of peat is part of the general subsidence of organic soil systems. These systems undergo subsidence from densification (loss of buoyancy, shrinkage and compaction); loss of mass (biological oxidation, burning, hydrolysis/leaching, erosion and mining) and direct loading (road construction, utilities, buildings and waste dumping) (Stephens et al., 1984; Cooke and Doornkamp, 1990; Wösten et al., 1997). The significance of the latter, which forms the focus of this chapter, needs to be viewed in the context of these other factors that have an impact on peat wastage. The best example of this in a UK context is the detailed record of peat wastage recorded at the Holme Post at Holme Fen (Figure 1) in the East Anglian Fenlands from 1848 to 1978 (Hutchinson, 1980, Waltham, 2000) (Figure 1). Using archival evidence Hutchinson (1980) was able to produce a precise chronology of lowering of the peat surface in relation to the Holme Post, a cast-iron column footed into clay below the peat, which served as a datum for evaluating surface changes. It was shown that land drainage using artificial pumps resulted in four distinct phases of surface lowering. During initial lowering shrinkage appeared to be the dominant factor in controlling surface lowering (0.2 m per year) as the bog was rapidly drained. However as time went on rates of lowering in the partially drained bog slowed (0.01 m per year) and biochemical oxidation became the predominant process. Such processes continue to affect these low lying peat soils resulting in risks to road subsidence (

Evaluating the relative importance of the factors resulting in mire surface lowering and compression is a complex problem and one which is common in many peatland settings. Kool et al. (2006) considered the importance of oxidation and compaction of a collapsed peat dome in Central Kalimantan caused by logging and agricultural drainage. Although they found it difficult to quantify these effects precisely they concluded that compaction appeared to be more important factor governing loss of peatland structure than oxidation. It is therefore important to acknowledge in any study of compressible peat soils that this is only one factor that governs the dynamics and stability of these complex organic soil systems.

4.2 Derrybrien Landslide, Wind farm construction, County Galway 2003.

The catastrophic peat mass movement that occurred at the Derrybrien wind farm development on 16 October 2003 captured the attention of all stakeholders with interests in the uplands and put on hold a wind farm industry that was rapidly expanding across many upland areas (Lindsay and Bragg, 2005) (Figure 7). The initial peat slide (estimated volume 450,000 m^3) failed on 16 October and travelled 2.5 km from the south-facing slope of Cashlaundrumlahan Mountain (365 m) originating in the vicinity of two partially constructed turbine bases (Figure 7a). The peat came to rest on 19 October at 195 m altitude but was re-activated by heavy rain on 28 October. It then moved another 1.5 km to the Owendalulleegh River where it became highly fluidised and continued to flow downstream into Lough Cutra, which was the source of the domestic water supply. The initial impacts along the downstream run-out track (Figure 7b)included loss of land, obstruction of roads, pollution of the domestic water supply and the death of an estimated 100, 000 fish (Lindsay and Bragg, 2005; Bragg, 2007).

Although engineering investigations were undertaken to evaluate the cause of the failure there was no clear conclusion reached amongst the consulting engineers. Investigations by peatland specialists however (Lindsay and Bragg, 2005) suggests that the failure may have resulted either from loading by excavation machinery or from the release of water into heavily-fissured peat or a combination of both. In addition loading due to the concrete turbine foundations also appears to have triggered local failures (Bragg, 2007) (Figure 7a). Following the incident at Derrybrien there was far greater awareness of the construction problems that are inherent when building on peat. Although these were well known elsewhere (MacFarlane, 1969) a greater consciousness was triggered in the UK resulting in much better planning and implementation of improved guidelines e.g. Guidelines for the risk management of peat slips on the construction of low volume / low cost roads over peat (MacCulloch, 2006; Munro and MacCulloch, 2006) and greater research into the mechanism that can trigger peat failures (Long, 2005; Dykes and Warburton, 2007; Long and Boylan; 2012).

4.3 Direct loading by quarry waste, Harthope Quarry, North Pennines UK

Figure 8 shows an historic RAF air photograph of Harthope Quarry, North Pennines UK (Figure 1) taken in June 1953. The image shows the area of the main quarry (A) and spoil / waste heaps which have been dumped on the surface of the adjacent blanket peat (B). The loading of the peat has triggered a series of six main peat failures (C) emanating from the quarry area. Peat depths in this area are approximately 1.5 m and the morphology of these failures is still evident on the ground today. Based on the air photograph evidence the type of peat mass movement appears to be a peat flow as described by Dykes and Warburton (2007) and is consistent with a head loading type failure implying that the rapid compression of the peat was significant in initiating this pattern of landslides. This is borne out by the general observation that 'peat slides' are a more common form of peat failure in the North Pennines (Warburton et al., 2004) and peat flows are unusual. Three key features, identified from Figure 8 give clues to the mechanism of peat failure. Firstly, the morphology is clearly a flow rather than a slide suggesting failure did not extend to the mineral substrate. Secondly the failure paths are relatively short (c. < 100m) and terminate in lobes suggesting these represent a local failure at the slope head (site of loading) whose flow path was rapidly attenuated downslope indicating the hydrological conditions necessary to promoting failure across the whole slope were not present (Warburton et al., 2004). Thirdly, the failures are adjacent to one another emanating from the point loading by the individual waste heaps at the head. This contrasts with the majority of peat slides in the region which general occur singularly along line of preferred drainage, although these may be loosely clustered in response to regional hydrological conditions (Evans and Warburton, 2007).

4.4 Failure during upland road construction, North Pennines, UK

Figure 9 shows a peat slide triggered by moorland road construction over an area of blanket peat, close to Burnhope Seat in the North Pennines, UK (Figure 1). The failure occurred in August 2006 during the construction phase of the road works. The floating road construction was excavated directly into the peat which in the vicinity of the failure was approximately 1.1 to 1.3 m deep, consisting of an upper fibrous peat overlying a more humified basal peat unit. The road was approximately 3.8 m wide and back filled with a coarse aggregate mix to a depth of about 0.5 m over a wire mesh which was laid in the construction trench.

Observations at the time of failure suggest that the aggregate truck which was hauling the road fill had just passed over the point of failure when the slope gave way and the driver was fortunate not to get caught up in the landslide. The failed mass slid down slope and entered the local stream course at the base of the slope discharging peat debris downstream into a drinking water reservoir. It is clear from the inset shown in Figure 9(b) that a 25 m section of road was transported down the slope during the failure from the top left to lower right of the picture remaining largely intact whilst in transit.

In this example the road was of a simple construction designed to be low cost for low volumes of traffic (mainly for shooting parties) but illustrates some of the potential challenges facing road building on peat. In this example, high water content, high compressibility and low strength all appear to be significant factors in the failure. Firstly, at the point of failure the road traversed a natural moorland 'flush' where the peat was slightly deeper and was very wet, even during the summer, due to preferred seepage of groundwater along the flush. Secondly, the construction method used conventional coarse aggregate to backfill the road excavation which was grounded in peat. This did not take advantage of using lightweight fill materials and it is estimated the haulage tricks were running 20 t loads over the newly constructed road with no period of consolidation (Munro, 2004). Thirdly, the peat in this locality consisted of approximately 0.7 m of fibrous peat over about 0.6 m of amorphous peat which overlaid a coarse stone clayey substrate. Approximately 0.3 m above the base of the amorphous peat there was pronounced water seepage zone which appeared to be the zone of the failure. Given these characteristics, it is clear the road was very unstable at this point along its route and failure was almost inevitable.

These three case studies clearly illustrate the importance of compressible soils in affecting hazards in upland peat areas and highlight the important interactions between human activities and sensitive peat soils. However, it is also worth emphasising that more subtle indirect actions on upland peat soils might modify the water table which can lead to additional problems. For example, in addition to compression caused by direct loading by engineering structures or waste, in natural and drained peatlands, changes in the height of the water table can cause changes in the effective stress which are large enough to significantly alter peat volume and alter hydraulic parameters (Price et al., 2005). However determining how peat compressibility relates to the physical properties of peat and the consequent hydraulic behaviour remains a complex task (Hobbs, 1986; Bell, 2000; Price et al., 2005). This is significant for hazard assessment in two main ways:
1) Soil testing of peat to determine the geotechnical and physical properties does not necessarily lead to an enhanced understanding of peat compression because these properties cannot be readily used to assess the hazard posed (see later discussion).
2) The sensitive relationship between water table fluctuations and peat consolidation is an important consideration when planning engineering structures over peat as water tables are frequently disturbed particularly during the construction phase. This may have immediate and possible long-term effects and as such represents a secondary hazard related to the primary hazard of direct loading of the peat surface (Munro, 2004).

5. Mitigation of the hazards posed by compressible peat soils

Peat is highly compressible and has a low bearing capacity and generally considered one of the worst foundation materials by practicing engineers. Typically, the costs of construction over peat are approximately 40% more expensive than over competent ground (Nichol, 1998), and ongoing maintenance/remediation costs can exceed initial project costs (Gould et al., 2002). Furthermore peat is highly heterogeneous and displays non-linear behaviour which often conflicts with theories and engineering practices used on mineral soils (Carlsten, 1988; Long, 2005).

In terms of mitigating the hazards posed by compressible peat soils three main approaches are possible:

1. Greater understanding of the properties of compressible soils and dissemination of good practice to engineers e.g. review of settlement of peat soils Long and Boylan (2014).
2. Non-structural mitigation such as land use zoning and development planning e.g. GeoSure (BGS, 2014).
3. Structural mitigation and improved engineering practice e.g. design of low volume roads over peat the ROADEX project (Munro, 2005; MacCulloch, 2006).

Long and Boylan (2013) provide one of the most recent reviews of predicting the settlement of peat soils. Their aim was to offer guidance to engineers who are required to make prediction of 1D compression of structures founded on peat and in particular identifies good practice in laboratory testing and the methods of calculation. Using a range of laboratory data (14 sites) and full scale loading case studies (five sites) they demonstrate that the $C\alpha/Cc$ law of compressibility generally applies and an average value for the compressibility ratio of 0.072 (Table 2). Long and Boylan concluded that although peat properties were highly variable, conventional staged construction with surcharge loading could be successfully applied to peat soils

These results to some extent confirm earlier laboratory testing by other engineers seeking to understand the in situ behaviour of peat as an embankment foundation material (e.g. Lefebvre et al., 1984). Geotechnical testing of peat samples in the laboratory is only one of a series of approaches used to determine the site characterisation of peat for engineering purposes (Edil, 2001; Long and Boylan, 2012). Edil (2001) concludes that a combination of methods using extensive sampling to define site variability; in situ tests (modified vane shear and penetration tests: Long and Boylan, 2012); laboratory testing for mechanical properties; and, where possible, the use of test fills (full scale loading test) provide a reasonable approach to dealing with problematic organic deposits (Magnan, 1994).

In the UK, engineers are well aware of the challenges facing construction projects over peat. An early example from Ward et al. (1955) describes a slip in a flood embankment in 1948 constructed over a thin peat layer as part of the River Don channel diversion scheme. More recently Nichol and Farmer (1998) describe the settlement problems associated with the main A5 trunk road as it traverses a peat bog at Pant Dedwydd in central North Wales. The road which was originally constructed in 1819 has suffered continuous maintenance problems and safety issues resulting from long term settlement. The solution has been to add successive layers of ashphalt which provide a short-term solution but only increase the loading which only adds to the problems in the longer-term. Nichol and Farmer (1998) using geotechnical tests confirmed the sensitive nature of the peat to compression and water loss (shrinkage) but also demonstrated that areas of extreme subsidence were associated with willow scrub patches growing in roadside ditches which contribute to subsidence by extracting water from the peat beneath the highway. Experience in Ireland is more widespread given the more common occurrence of peat across both upland and lowland environments (Long and Boylan, 2013). However, wherever peat occurs in small pockets or over entire regions engineers must be aware of its hazardous consequences (Nichol, 2001).

The British Geological Survey as part of its UK hazard assessment programme provides information about geological hazards and, in particular, the identification of areas which are susceptible to ground movement including compressible soils and peat (Figure 1a). Natural ground stability (GeoSure) national datasets provide geological information about potential for compressible ground to be a hazard. This assessment is based on 1:50 000 scale digital maps of superficial and bedrock deposits combined with information from the BGS Superficial Drift Thickness data and engineering reports. This is one of six different GIS layers, each representing a different potential natural ground stability hazard in Great Britain. Layers include: shrink swell (volume change in swelling clays); landslides (slope instability); soluble rocks (dissolution); collapsible deposits (when loaded); running sand (loosely packed sands fluidised by water); and compressible ground (soft materials that compress when loaded). For mapping compressible deposits, a digital geological map is used to select deposits with regard to their compressibility potential, e.g. peats and lake deposits are highly compressible, whereas bedrock is unlikely to be compressible (Royse, 2011). Each polygon from the digital map is then scored according to its susceptibility to compressibility. This was then combined with thickness of the superficial deposit and the two scores combined to give the overall hazard susceptibility rating (Royse, 2011).

Results translate in to five categories of hazard rating A-E (Table 4) and each category contains advice for the public and specialist on the appropriate actions and risk control measures that are potentially required. Typically, buildings constructed on compressible soils may experience structural damage to foundations; cracks in the walls, floors or ceilings, tilting of walls and strains or breaks in connections to water, gas and electricity supplies (BGS, 2014).

Table 4 near here

Engineering methods for peatland areas have evolved considerably over the last few decades and engineers now have a range of structural techniques and engineering practices at their disposal. These include: preloading and surface reinforcement; excavation and replacement methods; drainage systems; injection and deep mixing stabilisation; cement/stone columns; and geomaterials and lightweight fill (Huat et al., 2014). The choice of method differs depending on the nature of the construction project and the budget available. Typically, preconsolidation or preloading is used in road projects to increase shear strength and reduce the long-term compression of peat soils (Carlsten, 1988). The principle involves loading the peat with a load that is in excess of the final load that will be carried by the peat. This is allowed to settle until the design settlement of the planned load is reached. The excess load or surcharge is then removed and construction is then completed (MacFarlane, 1969). Some of the advantages of this method are that reduced fill material is used, peat excavation is not necessary and disposal of excavated peat is not required.

A good example where knowledge of loading methods is essential is in the construction of floating roads over peat. As part of the ROADEX Project, which is a technical cooperation between roads organisations across northern Europe, the engineering of low cost roads over peat was investigated. This is summarised in three reports which deal with bearing capacity problems on low volume roads constructed on peat (Munro 2004); provide guidelines for the risk management of peat slips on the construction of low volume/low cost roads over peat (MacCulloch, 2006); and provide a discussion of the main issues to be considered when planning rehabilitation measures for floating roads over peat (Munro and MacCulloch, 2006).

Collectively the three reports provide useful practical guidance for the local planners, construction engineers and road maintenance engineers that can be used to address common problems of peatland roads, and avoid the failure of such projects (see earlier example).

6. Conclusion

It has been demonstrated that peat is a highly compressible geological material whose consolidation and rheological behaviour is dependent on the permeability and distribution of water within the peat. Depending on the structure of the peat and degree of humification, the water content and type of water (intercellular, interparticular or adsorbed) this will influence the time-dependent behaviour of this type of organic deposit. It is also apparent that there is no single, simple relationship between the magnitude and rate of compression of peat and loading. Generalisations can be made about gross differences between broad peat types (fibrous versus amorphous peat) and some useful progress has been made in developing engineering guidelines but overall peat is intrinsically a complex and highly variable geotechnical material and as such adds uncertainty to our understanding of its geological hazards. Coupled to this source of uncertainty is the additional uncertainty that the extent of mapped peat deposits in the UK is subject to considerable error due to inconsistencies in the definition of peat soils between individual countries and differences in available data (JNCC, 2011). Hence different mapping agencies, steered by different objectives, produce different estimates of the extent and occurrence of significant peat deposit.

Mitigating compression and bearing capacity failure hazards in peat soils is therefore a difficult process, however, a combination of improved understanding of the properties of compressible peat; better mapping and land use zoning; and appropriate construction will mitigate risk. Therefore rather than rely on specific geographical knowledge of peat extent to guide local decisions, engineers and environmental scientists should be aware of the general occurrence of peat, be able to recognise it and have knowledge of its geotechnical / environmental behaviour so that appropriate strategies can be selected. Finally, failures resulting from peat compression are locally generated but due to the sensitive nature of blanket peat these can result in runaway failures that pose a far greater risk.

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Figures and Tables

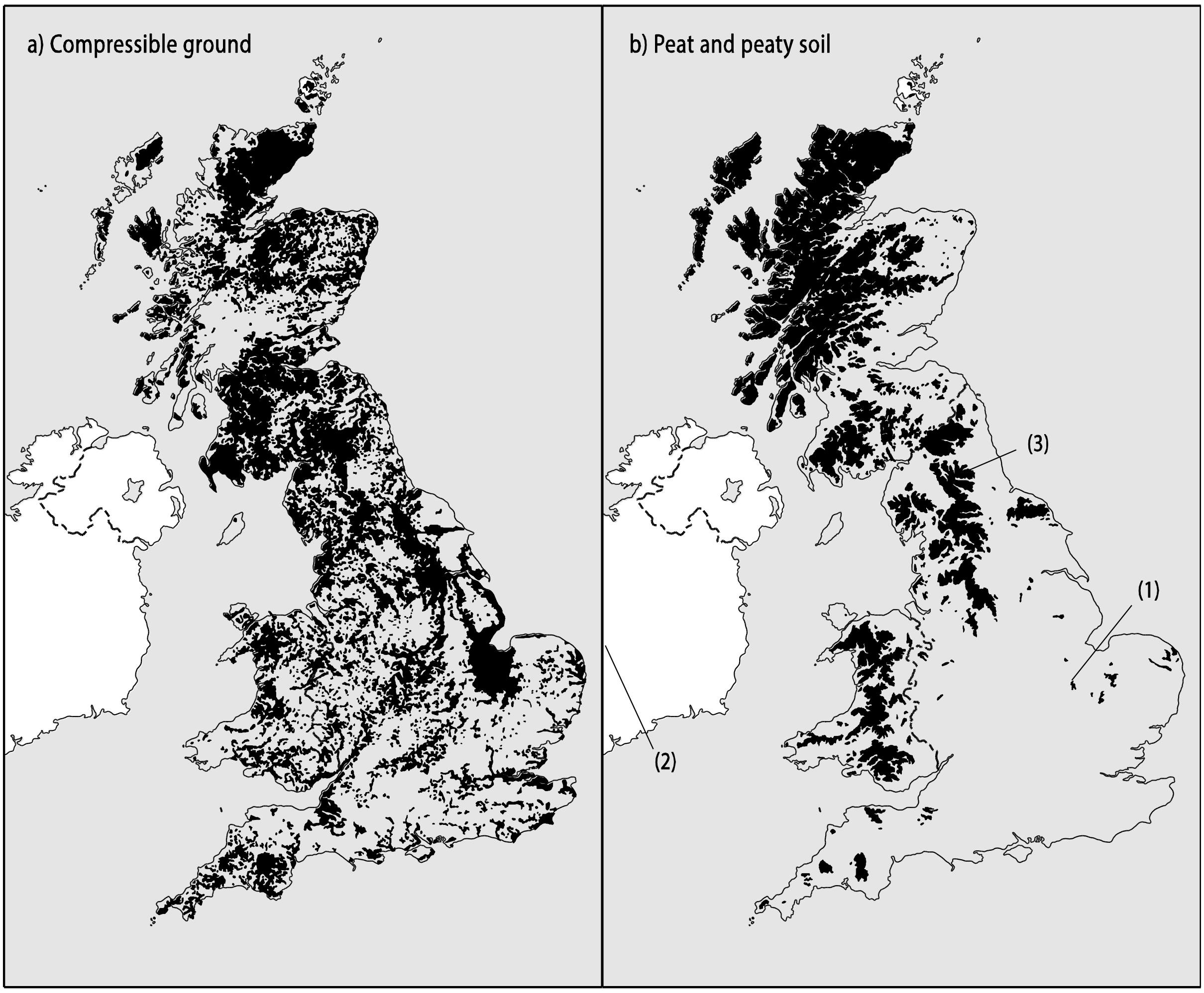

Figure 1. (a) Compressible ground potential map (map modified from British Geological Survey, 2014) (b) Peat and peaty soils of the United Kingdom (map modified from JNCC 2011). Numbers indicate key sites discussed in the text: (1) Holme Fen, (2) Derrybrien and (3) North Pennines (Burnhope and Harthope).

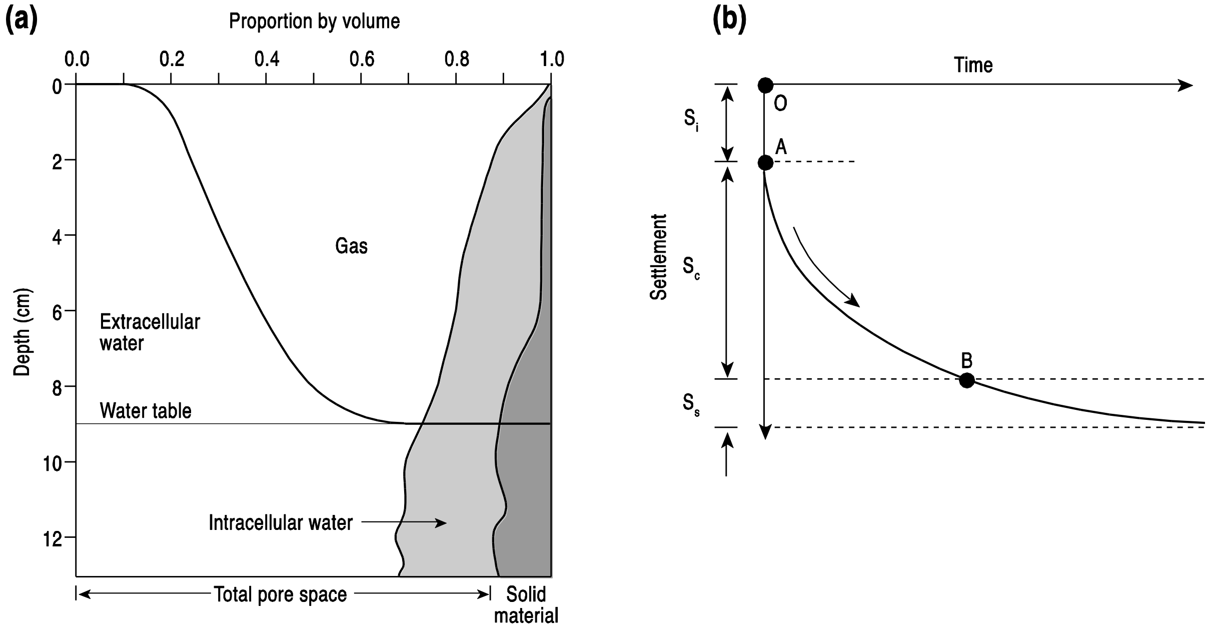

Figure 2. (a) Water, gas and solid material volume relationships in a peat core under *Sphagnum capillifolium* (b) Typical time settlement relationship for a saturated soil under a vertical load (modified from Rydin and Jeglum, 2006; Aysen, 2005)

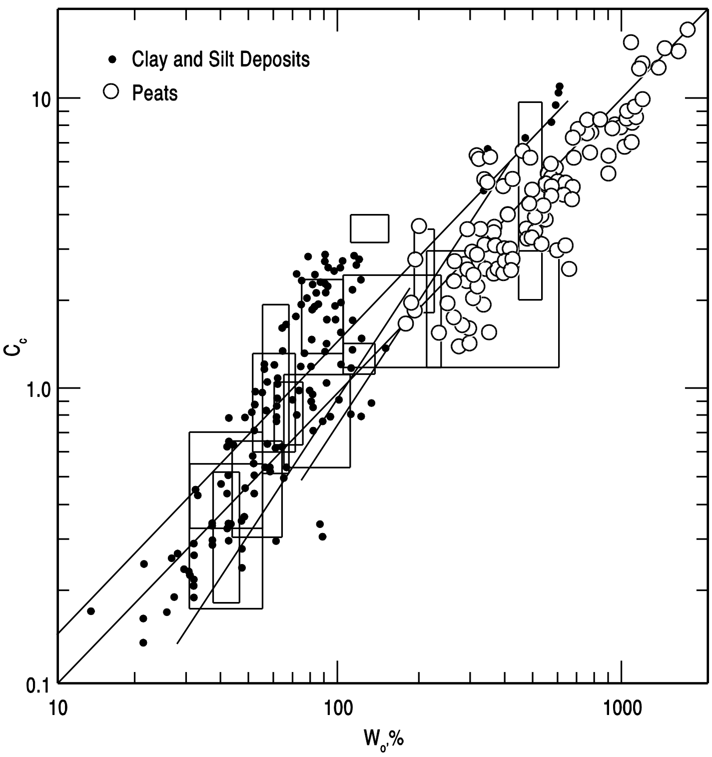

Figure 3. Plot of percentage natural water content (W_o) and compression index (C_c) for soft clay/silt deposits and peats (from Mesri et al., 1997).

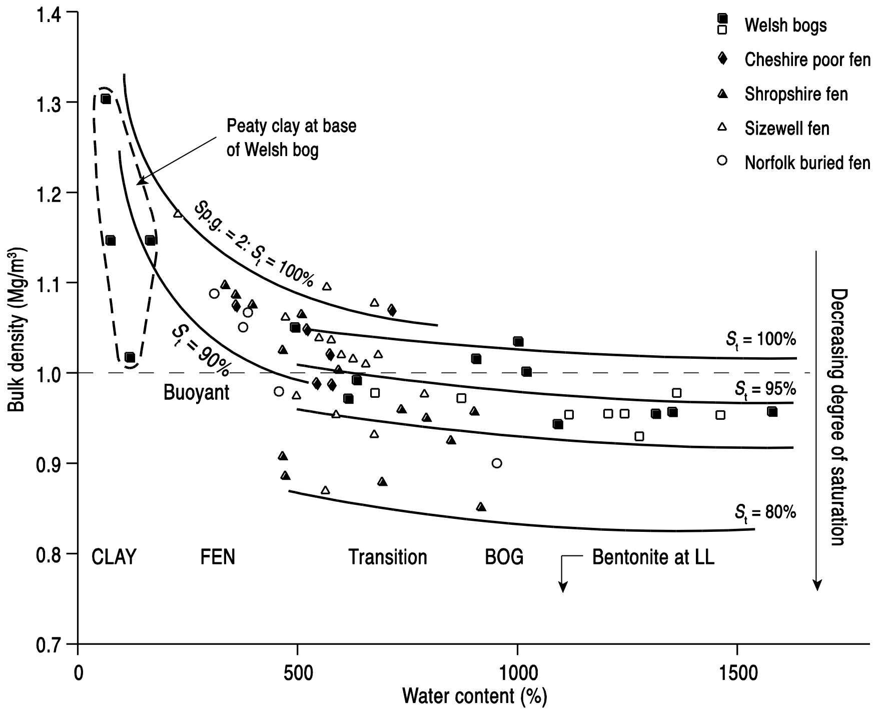

Figure 4. Variation of the water content (%) of UK mire peats with bulk density (After Hobbs, 1986).

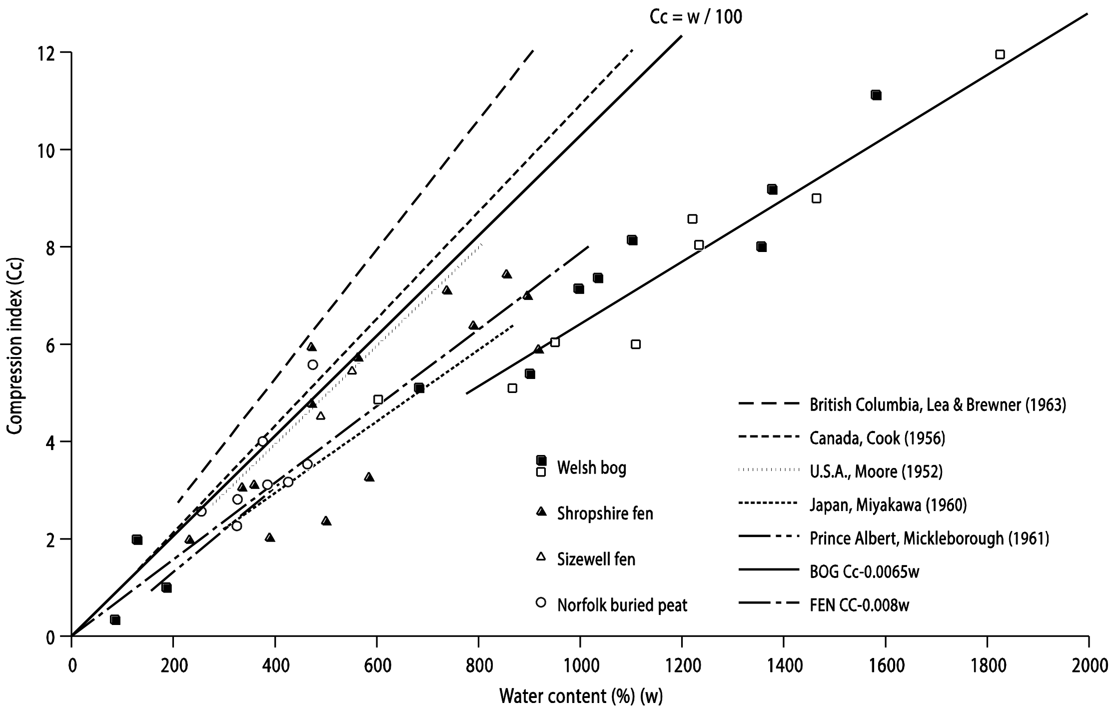

Figure 5. Variation in the compression index (Cc) in peat with water content (%). Comparison between UK fen and bog peat and other international examples (After Hobbs, 1986).

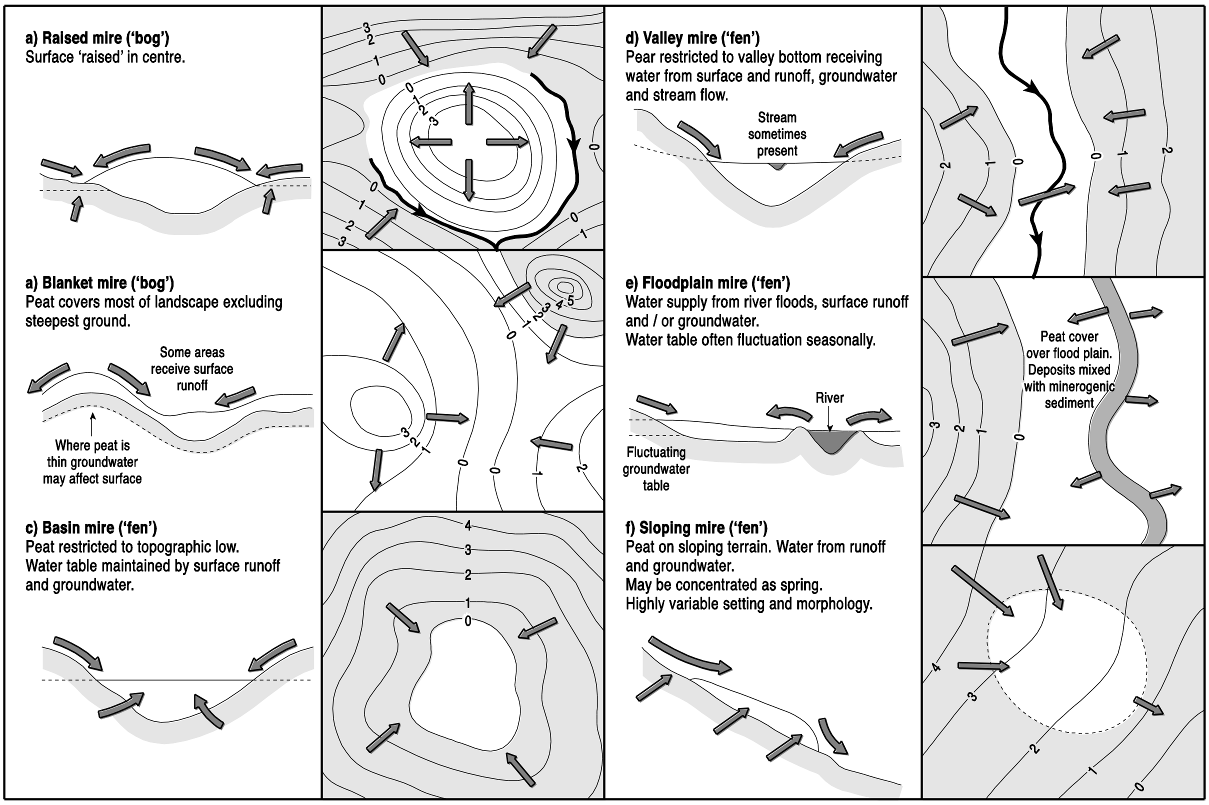

Figure 6. Illustration (cross-section and plan) of key hydromorphological mire types found in temperate peatlands like the UK (After Charman, 2002).

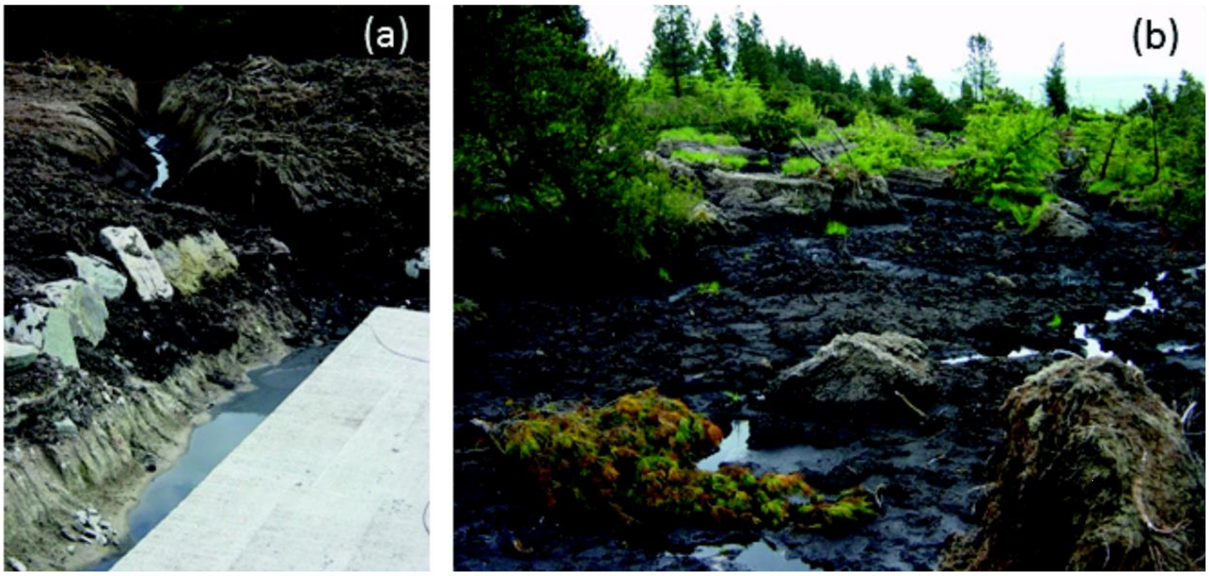

Figure 7. The Derrybrien wind farm development site. (a) Disturbed ground in the vicinity of a wind turbine foundation showing the exposed peat and mineral substrate. (b) The main landslide run-out track downstream of the failure site (Photographs courtesy of Olivia Bragg).

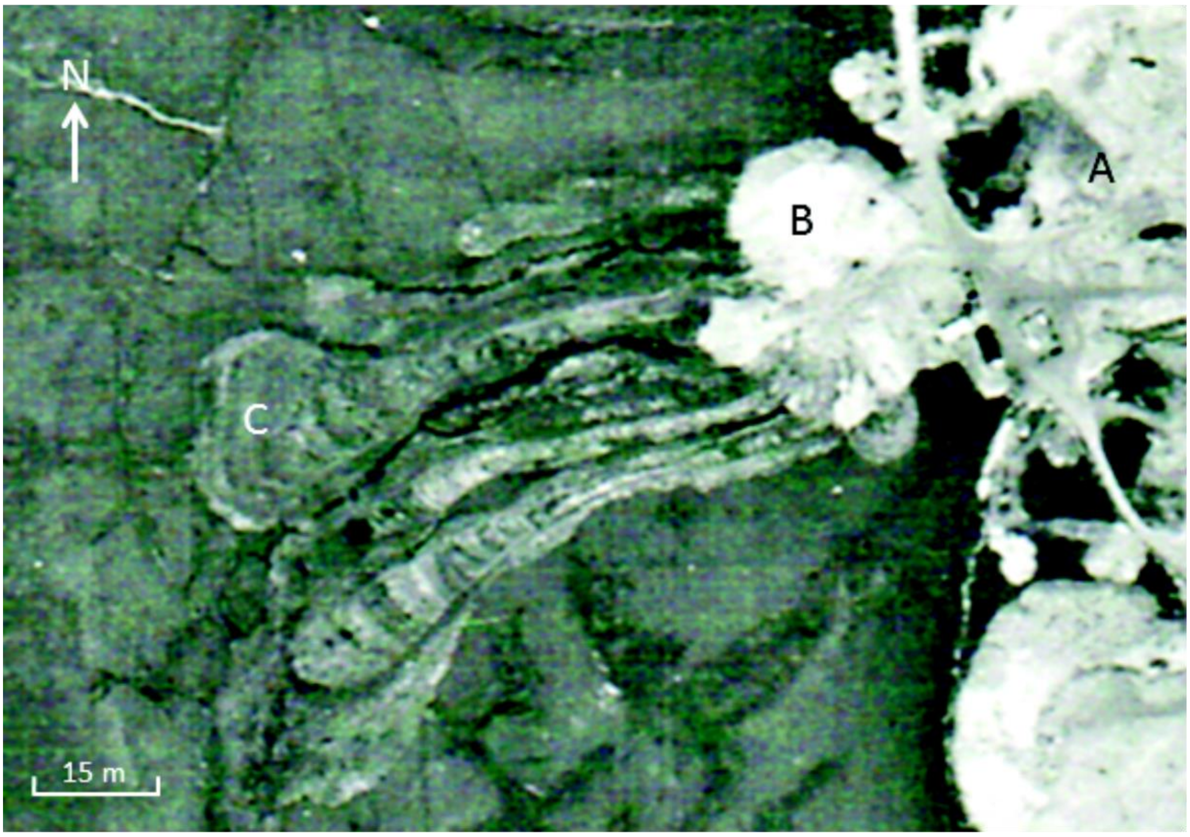

Figure 8. June 1953 RAF air photograph of Harthope quarry, North Pennines UK. The image shows the main quarry area (A) and spoil heaps which have been dumped on the surface of the adjacent blanket peat (B) resulting in a series of peat failures (C) due to the vertical loading.

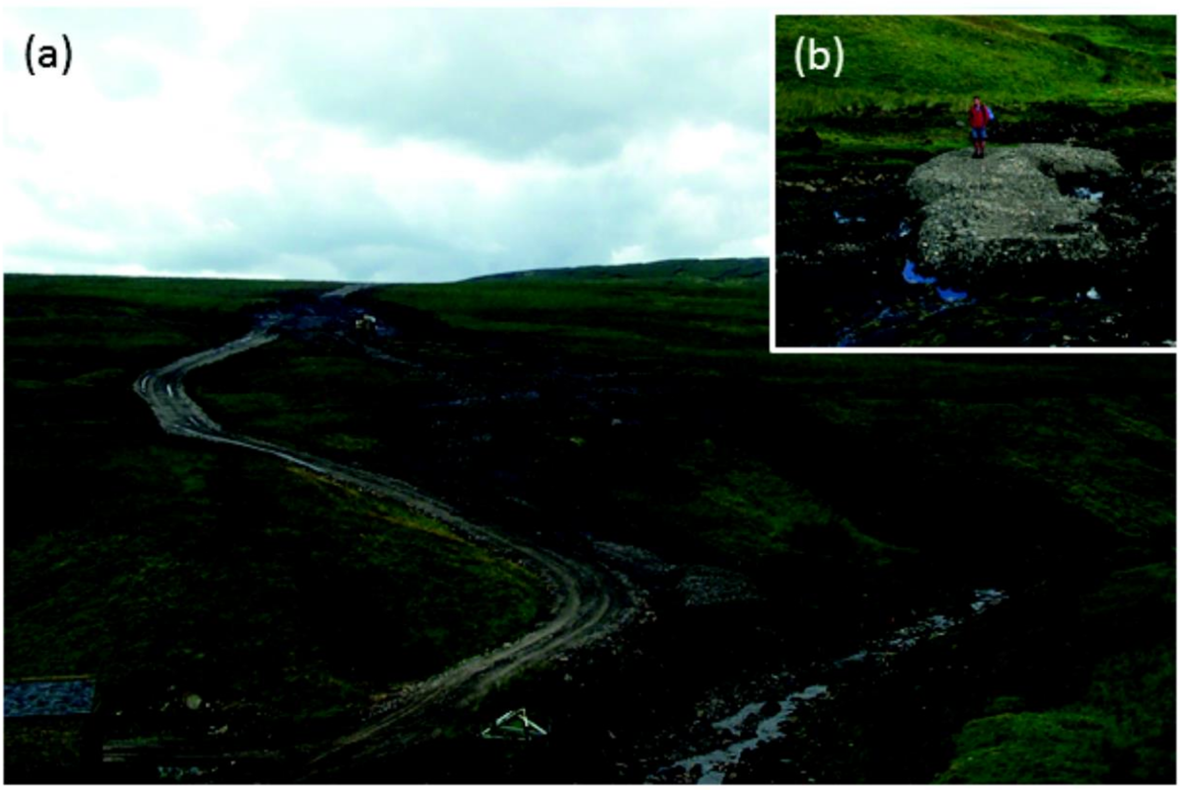

Figure 9. (a) A peat slide triggered by moorland road construction over an area of blanket peat in the North Pennines, UK. (b) Inset shows 25 m section of road which was transported down slope during the failure from the top left to lower right of the picture.

Table 1. Humification of peat (modified from von Post, 1922, Hobbs, 1986)

Degree of humification	Decomposition	Plant structure	Content of amorphous material	Material extruded when squeezing (passing between fingers)
H_1	None	Easily identified	None	Clear, colourless water
H_2	Insignificant	Easily identified	None	Yellowish water
H_3	Very slight	Still identifiable	Slight	Brown, muddy water; no peat
H_4	Slight	Not easily identified	Some	Dark brown, muddy water; no peat
H_5	Moderate	Recognisable, but vague	Considerable	Muddy water and some peat
H_6	Moderately strong	Indistinct (more distinct after squeezing)	Considerable	About one third of peat squeezed out; water dark brown
H_7	Strong	Faintly recognisable	High	About half 0f peat squeezed out; any water very dark brown
H_8	Very strong	Very indistinct	High	About two thirds of peat squeezed out; also some pasty water
H_9	Nearly complete	Almost unrecognisable		Nearly all of peat squeezed out as a fairly uniform paste
H_{10}	Complete	Not discernible		All peat passes between the fingers; no free water visible

Table 2. Peat properties and compressibility ratio data (modified from Mesri et al., 1997).

Peat Type	Water Content (% of dry weight)	Vertical coefficient of permeability (m s^{-1})	C_α / C_c
Fibrous peat	850	4 x 10^{-6}	0.06-0.10
Amorphous to fibrous peat	500-1500	10^{-7} – 10^{-6}	0.035-0.078
Canadian Muskeg	200-600	10^{-5}	0.090-0.10
Fibrous peat	613-886	10^{-6} – 10^{-5}	0.06-0.085
Fibrous peat	660-1590	5x10^{-7} – 5x10^{-5}	0.06
Fibrous peat	610-850	6x10^{-8} – 1^{-7}	0.052
Long and Boylan (2014) – Irish peat	c. 350-1000		0.072

Table 3. Summary of the extent of peat (organic-rich soils) (in ha) in the UK based on soil map data (modified form JNCC, 2011).

	Shallow peaty or organo-mineral (ha)	Deep peaty or organic soils (ha)	Total peaty soils (ha)	% of UK land area
England	738 618	679 926	1 418 544	5.8
Wales	359 200	70 830	430 030	1.7
Northern Ireland	141 700	160 902	302 602	1.2
Scotland	3 461 200	2 326 900	5 788 100	23.6
TOTAL	4 700 718	3 238 558	7 939 276	32.3

Table 4. British Geological Survey compressible ground hazard rating key (BGS, 2010; 2014).

	Hazard rating	Advice for public	Advice for specialist
A	No indicators for compressible deposits identified.	No actions required to avoid problems due to compressible deposits.	No special ground investigation required or increased construction costs or increased financial risk due to potential problems with compressible deposits.
B	Very slight potential for compressible deposits to be present.	No actions required to avoid problems due to compressible deposits.	No special ground investigation required. Unlikely to be increased construction costs or increased financial risk due to potential problems with compressible deposits.
C	Slight possibility of compressibility problems.	Take technical advice regarding settlement when planning extensions to existing property.	**New build** — Consider possibility of settlement during construction due to compressible deposits. Unlikely to be increase in construction costs due to potential compressibility problems. **Existing property** — No significant increase in insurance risk due to compressibility problems.
D	Significant potential for compressibility problems.	Avoid large differential loadings of ground. Do not drain or dewater ground near the property without technical advice.	**New build** — Assess the variability and bearing capacity of the ground. May need special foundations to avoid excessive settlement during and after construction. Consider effects of groundwater changes. Extra construction costs are likely. **Existing property** — Possible increase in insurance risk from compressibility if lowered groundwater levels drop due to drought or dewatering.
E	Very significant potential for compressibility problems.	Avoid large differential loadings of ground. Do not drain or dewater ground near the property without technical advice.	**New build** — Assess the variability and bearing capacity of the ground. Probably needs special foundations to avoid excessive settlement during and after construction. Consider effects of groundwater changes. Construction may not be possible at economic cost. **Existing property** — Probable increase in insurance risk from compressibility due to due to drought or dewatering unless appropriate foundations are present.